The VLA Expansion Project: Phase II Overview

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1 Scope

The primary goal of Phase II of the VLA Expansion Project is to expand the VLA's resolution by a factor of ten, while maintaining the image fidelity of the present instrument. These will be accomplished by incorporating (two or more) nearby VLBA antennas, and adding new stations at distances of up to ~ 300 km from the array center. All stations will be connected by fiber optic lines to the WIDAR correlator, whose current design will permit incorporation of up to 40 full-bandwidth inputs. More than 40 inputs are possible (thus permitting real-time operation of the entire VLBA, for example) at reduced bandwidth.

Additional goals of Phase II may include:

i) Coverage of frequencies below 1 GHz

ii) Construction of a super-compact ('E') configuration

iii) More extensive incorporation of the VLBA as a real-time system.

Incorporation of these additional goals will depend on scientific priorities and projected costs. It should also be kept in mind that there are viable means for including the low-frequency goals into Phase I (very wideband feeds), but possibly at the cost of a significant decrease in the sensitivity at higher frequencies.

2 The Baseline Plan

This includes all three of the goals listed above. Some more details are now given.

2.1 The New Mexico Array

The baseline plan includes two VLBA (PT and LA) and eight new 25m antennas, located at distances up to 250 km. The selection of 8 was made purely on a combination of intuition and rough costs (i.e., 4 will give poor imaging performance, 15 will cost way too much, thus 8 sounds about right). Rough estimates of imaging performance and costs do justify these intuitions, but also show that 'more is better'. The baseline plan assumes these new facilities take the form of 25-meter antennnas – there are both advantages and disadvantages of station arrays.

A major uncertainty is the means of connecting these antennas to the correlator. Fiber is of course a virtual certainty, but whose fiber, and the costs of access and of burial, need to be established before a firm design can be made.

The NMA configuration can assume a number of forms. The following tables show the point-source and brightness sensitivity for a 37-element array consisting of the existing 27 VLA antennas, two existing VLBA antennas (PT and LA), and eight new antennas distributed in two rings, two on an inner ring and six on an outer ring. The best sensitivity is achieved with natural weighting, while the best resolution is achieved with uniform weighting. The strong (and unavoidable) central concentration of antennas results in a wide variation in resolution and imaging performance as a function of the u-v weighting. The best overall imaging capability is achieved by weighting the data with a robustness of ~ -1. Using natural weighting will lower the resolution by a factor of three, and increase the sensitivity by about 50% (and thus increase the surface brightness sensitivity by a factor of about 15!). It also greatly degrades the imaging performance. Increasing the 'robustness' parameter from -1.0 to $+0.5$ will reduce the resolution by a factor of 1.7, and improve the sensitivity by about 25%, thus giving about four times the surface brightness sensitivity. This combination will maintain good imaging characteristics.

Table 1: **New Mexico Array (37 antennas) - Continuum Properties**

Frequency (GHz)	$\Delta\nu$ (GHz)	Resolution (marc)	Point Source rms (μJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	0.10	800	660	36	22,000	1190
0.30–0.45	0.10	500	320	17	11,000	550
0.45–0.70	0.20	340	150	8.1	4,900	270
0.70–1.10	0.50	220	65	3.3	2,100	110
1.10–2.00	1.0	125	33	1.8	1,000	60
2.00–4.00	3.0	64	20	1.1	660	36
4.00–8.00	6.0	32	15	.75	500	25
8.00–12.00	6.0	20	17	.90	560	30
12.00–18.00	8.0	13	18	.90	600	30
18.00–26.50	12.0	9	22	1.1	725	36
26.50–40.00	16.0	6	20	1.0	660	33
40.00–50.00	10.0	4	43	2.3	1420	76

Two other forms of the NMA configuration are of practical interest. The proposed eight-

Table 2: **New Mexico Array (37 antennas) - Spectral Line (1 km s^{-1}) Properties**

Frequency (GHz)	$\Delta\nu$ (kHz)	Resolution (marc)	Point Source rms (mJy/beam)		T_b rms (K)	
	Dual pol.		2 min	12 hr	2 min	12 hr
0.20–0.30	1.7	800	160	8.8	5.3×10^6	2.9×10^5
0.30– 0.45	2.5	500	64	3.2	2.1×10^6	1.1×10^5
0.45– 0.70	3.8	340	35	1.9	1.6×10^6	62,000
0.70– 1.10	6.0	220	19	0.94	6.0×10^5	31,000
1.10– 2.00	10	125	10	0.56	3.4×10^5	19,000
2.00– 4.00	20	64	7.7	0.43	2.5×10^5	14,500
4.00– 8.00	40	32	5.8	0.29	1.9×10^5	9,600
8.00– 12.00	67	20	5.1	0.27	1.7×10^5	8,900
12.00–18.00	100	13	5.0	0.25	1.6×10^5	8,300
18.00–26.50	148	9	6.3	0.31	2.1×10^5	10,000
26.50–40.00	222	6	5.4	0.27	1.8×10^5	8,900
40.00–50.00	300	4	7.7	0.41	2.5×10^5	13,500

antenna, two-ring arrangement will give outstanding imaging characteristics when used as a stand-alone array, or as an array with one or more VLA antennas added. For the case of an eleven-element array (ten antennas in two rings, plus a single VLA antenna), the sensitivity will be worsened by a factor of 2.7, and the resolution will be improved by 40% compared to the entries in Tables 1 and 2, thus lowering the brightness sensitivity by a factor of five from the tabled entries. For the case of a 14-element array, comprising the ten antennas in two rings, plus four VLA antennas (one at the center, and one each at the ends of the arms of the A-configuration), the sensitivity would be worsened by a factor of 2.2, and the resolution improved by about 35%, leading to a decrease in surface brightness sensitivity by a factor of about 4. For both of these arrangements, the resolution and sensitivity can be traded off by about 15% by adjusting the weighting.

2.2 Low Frequencies

The lowest frequency addressed in Phase I is about 1.0 GHz, a limit set by diffraction, and by the assumed use of the current subreflector. Accessing lower frequencies will require either a means of accessing the prime focus, OR a new subreflector and feed system. In summary, there are three ways to incorporate low frequencies (below 1 GHz):

a) Devise a way to move the existing subreflector out of the way, and incorporate a prime focus (PF) feed system. This would require modification of the quadrupod feed legs, and a rotating or translating mount system to remove the subreflector and position a PF feed. This would be something like the new WSRT system.

b) Design a new subreflector, which could be as large as twice the existing subreflector. This would lower the lowest frequency which can be accessed from the secondary focus by the same factor (i.e., to perhaps 500 MHz), but would require new quadrupod legs and mounting. A significant disadvantage would be that it is unlikely such a subreflector would be moveable, so that prime focus operation would not be possible: frequencies below 500 MHz will be forever lost. An advantage is that all the higher frequency bands could employ smaller feeds, thus freeing up space around the feed ring (and possibly offering better performance over each of the bands).

c) Employ a 'Jack Welch'-style broadband feed system, to cover the full frequency range from ~ 500 MHz to 5 GHz in a single band. However, as this feed's primary lobe is broader than the current angle seen by the subreflector at the Cassegrain focus, the feed would have to be mounted much higher than the current focus, and a new subreflector, designed to this new focus, would have to be designed and built. This would require all-new feeds for all high-frequency bands. It also seems that the main-beam efficiency of this 'JW' feed is lower than a modern horn, that ohmic losses are high, and that polarization performance is poor. The higher frequencies would also still have to be covered by separate feeds.

2.3 Super-Compact ('E') Configuration

There is a large gap between the VLA's D configuration (maximum baseline=1.2 km) and single dishes like the Green Bank Telescope (GBT; diameter 100 meters). We could fix this by building a more concentrated 'E' configuration, with maximum baselines ~ 300 m. This new configuration would probably be used quite often in 'mosaic' mode to map regions larger than a VLA antenna's primary beam allows in a single pointing. In such cases GBT data could be added to complete the uv-coverage down to 0 spatial frequency. The images produced would have three times higher resolution than the GBT by itself, with good surface brightness sensitivity and high fidelity.

The existing D configuration can be 'tapered' down to cover this range of spatial frequencies, but the synthesized beam pattern produced this way has very high sidelobes and thus is not very good for high-fidelity imaging. An E configuration would be much more sensitive to extended emission, but the most important advance would be in very high quality imaging of large, complex regions.

2.4 Real-Time VLBA

The EVLA proposal, and the presentations of the EVLA to the Decadal panel, contained no mention of incorporation of the VLBA into the EVLA plan. However, in light of rapid developments in wide-band fiber-optics, and of developments in real-time VLBI being done in the US and Japan, it is proper to consider a 'real-time' VLBA capability as one of the EVLA's goals, if this can be done without jeopardizing the other goals. At a minimum, we must ensure that we don't 'design out' this important capability. There are real, tangible scientific benefits to a real-time VLBA which utilizes some/all of the Phase II antennas.

3 Budget and Time Considerations

The Decadal Panel recommendation was for $140M for the entire VLA Expansion Project — both phases. However, this is not a fixed target, only a suggestion based on information provided to the panel during the presentations made early in 2000. What is important are the expected science gains for the money we propose to spend.

Our early rough budget for the NMA portion of Phase II was $70M. To this would be added approximately $5M for the low-frequency system and E configuration, which in an earlier version of the proposal were included in Phase I.

It is important that Phase II be completed expeditiously. No firm time estimate was given in the presentation to the Decadal Panel, but in light of SKA plans and developments, and from the point of view of the science, a time goal of completion within this current decade would seem prudent. This will require a proposal to the NSF within a year or two, at the latest, for any chance of funding sufficiently early to permit completion by 2009.

3.1 Interaction with Phase I Developments

Phase I of the VLA Expansion Project has already begun, and that imposes some important constraints on Phase II planning. The most important of these are as follows:

- *Subreflector modifications:* Phase I involves a major upgrade to the VLA feeds, including the construction of several entirely new receiver systems. Enlarging the subreflector to extend the low frequency coverage below 1 GHz, or switching to a 'Jack Welch'-style broadband feed, would require significantly different feed designs for Phase I. It is therefore highly desirable to decide whether to follow one of these options by the time preliminary design review for the Phase I feed cone/receivers (currently set for January 2002); and we *must* have made that decision by the time of the critical design review (currently set for January 2003).
- *Correlator expansion:* The most obvious approach to correlating the 37 stations envisioned in the baseline plan for the NMA would be to use an expanded version of the WIDAR correlator being built for Phase I. Further expansion, to 48 stations or more, could accommodate real-time VLBI as well. It would be highly beneficial to order all the hardware (chips etc.) for this correlator at the same time; indeed, if we waited too long, the devices the boards were designed for will no longer be available. This means we would like to know the size of the final correlator by December 2005 (when the chip run begins), and *must* know that by perhaps a year later.
  Of course one could design a totally new correlator for Phase II, but this would involve several additional years of design effort (and consequent delay), and lead to the unpalatable prospect of either junking the Phase I correlator shortly after it becomes operational, or significantly delaying access to Phase I's wider bandwidths while waiting for the arrival of the Phase II correlator.
- *Availability of astronomers:* Testing the Phase I hardware will involve many on the astronomical staff in Socorro, starting in about 2003, and ramping up from that point. This argues for

working on the Phase II proposal & development work soon, since those activities will also require significant scientific input.

- *Availability of engineers:* Phase I will demand almost all of the time of the VLA engineers, from now until the major design work is completed. Current timelines suggest that significant engineering manpower will become available in March 2004. Of course with sufficient funding one could hire more engineers (assuming they are available), but there is certainly a strong argument for waiting until the experienced engineering talent already on-hand becomes available.

Note also that we have already requested Phase I funds for proto-typing a rotating subreflector, as would be needed for one of the low-frequency designs. This is currently scheduled for March 2004.

Table 3 shows the current (draft!) timeline for Phase I of the VLA Expansion Project, pointing out important *breakpoints* and **deadlines** for Phase II decisions.

Table 3: **Draft Timeline for the VLA Expansion Project.**

Date	**Activity**
1 May 01	Official beginning of EVLA Phase I
Aug 01	*EVLA Planning Workshop: Defining the Second Phase*
Sep 01	*EVLA Phase II proposal decision:* whether to request R&D or construction funds, & when to submit the proposal
Jan 02	*Feed cone/receiver PDR:* breakpoint for deciding on subreflector modifications
	First draft of EVLA Phase II Design Study
Aug 02	Start installing fiber on array. No antennas connected.
Jan 03	*Feed cone/receiver CDR:* **deadline** for deciding on subreflector modifications
	Earliest possible funding for EVLA Phase II research & development
Apr 03	Choose EVLA Test Antenna near array center. Install new IF/LO/FO system.
	Test with new prototype M/C system. Some new and some old front-ends.
	Not available for observing.
Jul 03	Start interferometry tests between EVLA Test Antenna and VLA.
Oct 03	Freeze electronics design. Start electronics production.
Jan 04	*Earliest possible funding for EVLA Phase II construction*
Mar 04	Start installation of new IF/LO/FO system on antennas at 7 antennas/year.
	Full M/C capabilities available. EVLA antennas available for observing.
	Start installation of highest priority new front-ends.
	Subreflector proto-typing (funded by Phase I)
	Engineers become available for EVLA Phase II work!
Q3, 05	1–3 element correlator available for testing at the VLA.
Late 05	*Plausible date for beginning EVLA Phase II construction* if we don't hire more engineers for development work
Dec 05	*Correlator chip production run begins:* breakpoint for deciding on size of correlator
Dec 06	*Last-chance* **deadline** *for deciding on size of correlator:* set jointly by
	(1) our ability to get the devices that the boards were designed for; and
	(2) ramping down of Phase I correlator development (upper level correlator people could be retained, at some cost...)
Q4, 07	Start installation of new correlator in new correlator room at VLA.
Q1, 08	New correlator available for beta testing.
Mar 08	Last antenna converted to EVLA design.
Q1, 09	New correlator on-line, start testing.
Q4, 09	New correlator debugged & fully operational.
May 10	Last new receiver installed.